Spin-lock based magnetic field sensing: a non-invasive MRI method for spatially resolved imaging of cardiac conduction?

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Introduction: We present a novel method enabling spatially resolved detection of ultra-weak magnetic signals by means of standard clinical MRI. For this purpose, we exploit the particular condition of spin-locked magnetisation, which shifts the sensitivity of the MRI device from the MHz to the Hz range [1]. In this state, low-frequency magnetic oscillations lead to rotary excitation (REX) and can even be detected in the nT-range [2]. The following study presents the customisation of this approach to QRS-like fields, with the objective of paving the way for direct imaging of cardiac conduction in humans.

Theory: The direct, spatially resolved detection of magnetic fields is accomplished by irradiating a spin-lock (SL) field, which rotates the tissue magnetisation at frequency $f_{SL}$, followed by a rapid image acquisition. We assume that the interaction of the spin system with a magnetic signal during SL is resonant if the Fourier transform of this signal fits within the range of $f_{SL}$ (Fig. 1a-b). In this case, a sinusoidal NMR signal is expected with a variation of the interaction timing, which is evaluated after imaging and whose amplitude $AREX$ is used for field detection.

Methods: The new detection principle was validated with externally generated field fluctuations in a phantom experiment on a clinical 3.0T MRI system. In the first step, simple waveforms with well-defined frequency spectra were analysed. $AREX$ was determined from the standard deviation of the observed signal oscillation. By varying $f_{SL}$, the resonance effect was successively investigated. Subsequently, a QRS-like field whose waveform models MCG measurements was considered [3]. The sequence parameters were optimised for a QS duration of 100ms. Detection was attempted for peak amplitudes in the range 5...100nT.

Results: Fig. 1c) presents exemplary MR images used for field detection. Fig. 2a-b) show the investigation of the resonance effect for different signals. Magnetic peaks of varying waveforms can be clearly distinguished on the basis of their characteristic response for SL frequencies. Fig. 2c-d) show the results of the first detection trial of an artificial QRS. The observed signal follows a sinusoidal course, which is clearly different from the reference measurement (Fig. 2c). The detected $AREX$ increases linearly ($R^2 > 0.99$) with the amplitude of the QRS peak (Fig. 2d).

Discussion: This work presents a new approach for direct sensing of magnetic signals using MRI. The results demonstrate a high sensitivity in the nT-range, which is sufficient for cardiac fields [4]. Furthermore, spectral properties of magnetic signals can be probed. Therefore, our REX method potentially holds promising applications for non-invasive quantitative diagnosis of cardiac function. However, transfer of the well-controlled phantom experiment to the in vivo setup is expected to face major challenges due to motion and blood flow, and will require superb shimming of the main magnetic field.

Figure 1) Concept of QRS detection

a) pulse sequence diagram
b) magnetisation trajectory during SL interaction (REX)
c) MRI magnitude images

Fig. 1a) Concept of magnetic field sensing for QRS detection.

b) During the application of a spin-lock pulse, the tissue magnetisation can interact with a QRS-shaped magnetic field. Significant deflection of the trajectory only occurs in the resonance case.

c) Magnitude images for different interaction timings in phantom experiments. The detected signal amplitude depends on the interaction timings and can be clearly distinguished from offresonant reference scans.
Fig. 2 Field detection results in the phantom experiment. Results for gaussian a) and sinc-shaped b) fields. The REX experiment shows a high sensitivity to the spectral components of the investigated fields and can clearly distinguish different signals.

c) - d) Detection of artificially generated QRS-like fields. In all experiments, a QS duration of 100ms and resonant SL Pulse (f_SL=10Hz) were used.

c) The detected signal is clearly enhanced compared to the reference scans (QRS switched off).

d) Variation of the QRS-peak amplitude. The REX amplitude increases linearly with the QRS field strength (R²<0.99).